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HOLOGRAPHIC MULTIPLEXING FOR 3D OPTICAL MEMORY

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June 1993

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13. ABSTRACT *(Maximum 200 words)*

The increasing demand for larger memory capacity has led to the exploration of volume data storage in optical materials with theoretical capacities of 10^{13} bits/cm^3. However, an important technical barrier is the design of an input/output architecture to read and write to the optical 3D memory at very high speed. During Phase I of this effort, we have experimentally demonstrated the operation of a unique optical lock-in instrument that can play a key role in accessing optical memories at high data rates. This optical lock-in detector is capable of demultiplexing a highly complex wavefront consisting of a number of holograms that have been combined on a single light beam. Using the optical lock-in detector, it is possible to demultiplex and recover any individual hologram using optical mixing in a photorefractive medium with the appropriate modulation applied to the reference optical beam. For Phase II a prototype optical memory system is proposed, including highly parallel input/output techniques, a cache memory for faster access, and a unique photorefractive material for optical data storage. At least one key component of this optical memory system, an optical beamlet array generator, is a likely candidate for Phase III development by Foster-Miller and Polaroid Corporation.

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1. INTRODUCTION

The increasing demand for larger memory capacity generated by the development of faster and more powerful computers has led to the exploration of new techniques for large-scale data storage. Volume data storage in optical memories is particularly promising with the theoretical capacity of 10^{13} bits in a volume of only 1 cm^3. However, in order to achieve this theoretical capacity, several major technical barriers must be overcome, including the development of appropriate optical materials for data storage and the design of an input/output architecture to read and write to the three-dimensional memory at very high speed. During Phase I of this effort, we have experimentally demonstrated the operation of a unique optical lock-in instrument that can play a key role in accessing optical memories at high data rates. In addition, based on parallel research efforts in optical storage materials and dynamic holography at Foster-Miller, we will propose for Phase II the construction of a prototype optical memory system, including highly parallel input/output techniques, a cache memory for faster access, and a unique photorefractive material for optical data storage. Phase III development of at least one key component of this optical memory system, an optical interconnect beam generator, may be carried out jointly by Foster-Miller and Polaroid Corporation.

The effort in Phase I concentrated on experimentally demonstrating the operation of an optical lock-in detector that is capable of demultiplexing a highly complex wavefront. For many applications, this wavefront consists of a number of holograms that have been combined or multiplexed onto a single light beam using a phase modulation applied to each hologram at a distinct frequency. Using the optical lock-in detector, it is possible to demultiplex and recover any individual hologram using optical mixing in a photorefractive medium and the appropriate phase modulation applied to the reference optical beam. Figure 1 illustrates the use of the photorefractive optical lock-in with an incident laser beam containing several multiplexed holograms. The basic operation of the optical lock-in technique can be understood by comparison with electrical lock-in operation. A conventional electronic lock-in detector consists of a frequency mixer followed by a low-pass filter. Mixing two frequencies f_1 and f_2 results in several new frequencies, including the beat frequency, $f_1 - f_2$, which can be recovered by low-pass filtering. It has been shown theoretically that the frequency multiplication part of this sequence can be carried out optically using photorefractive four-wave mixing. The slow response of the photorefractive material then provides the low-pass filtering (1).

Previous work in this area has been carried out at the Air Force Rome Laboratories (2,3) (Reference (2) is included as Appendix A for the convenience of the reader.) Researchers there have studied this basic technique for a number of applications, including direct replacement of electronic lock-in instrumentation for optical signals and studying images buried in noise. In our effort we have demonstrated the ability of the optical lock-in to demultiplex laser beams which contain multiple holograms and which therefore are capable of carrying large amounts of information at very high data rates. This feature is particularly useful for optical interconnection to large-scale optical memories.

1.1 Accessing Large Capacity 3D Optical Memories

While the photorefractive optical lock-in detector has several promising applications, we have chosen to focus on the rapid accessing of optical 3D memories, due in part to several ongoing programs at Foster-Miller in optical

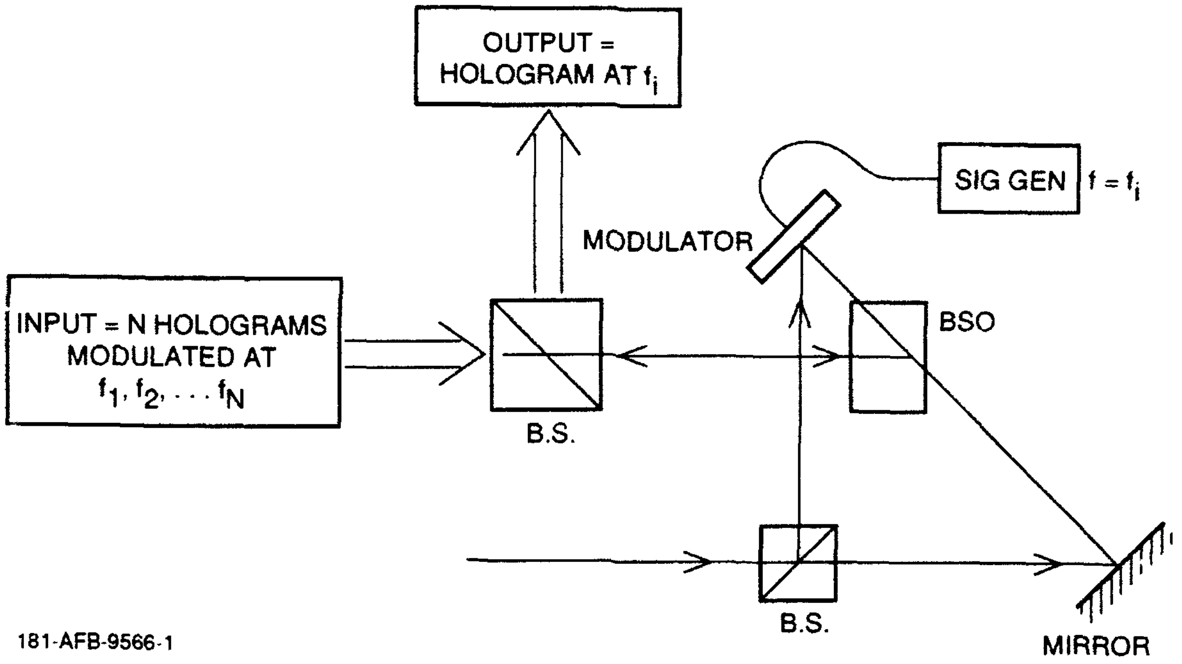

Figure 1. Basic operational configuration of the optical lock-in detector as a demultiplexer. A single hologram is selected from an incident beam containing N holograms using photorefractive mixing

storage and optical interconnects for 3D memories. In order to access large capacity memories at reasonable data rates, research to date has focused on parallel addressing methods. Two competing schools of thought are prominent at the present time. The first is the bit-oriented method, which is an extension of current methods of addressing data in 2D media such as magnetic disks. This research can be represented best by the work of the Irvine-San Diego group on two-photon memories which uses a parallel readout to produce rates on the order of 10^6 bits per access. However, there are some important limitations imposed by the requirement of a high-performance dynamically focusable lens (4).

The second school of thought, which we have adopted in our research, is the holographic-oriented method. In this approach, the stored unit of information is in the form of a hologram instead of localized bistability. Many holograms are stored in an optical memory media, and the reconstruction of each is used to access the information from its stored format. In theory, this method has the same capacity as the bit-oriented, but uses more developed technologies. Recently, researchers have been able to store up to 500 holograms in a crystal of $LiNbO_3$ (5,6). In most cases, the holograms are angle multiplexed in the storage media, although other variations such as wavelength multiplexing (7) and orthogonal phase holograms have also been used in an attempt to reduce cross talk.

The application of the lock-in detector that we have pursued is based on a conversion of angle multiplexed stored holograms to temporal multiplexed reconstructions. Access to a desired hologram is then accomplished via the optical lock-in detector which facilitates temporal demultiplexing of complex wavefronts (i.e., holograms). The result, illustrated in Figure 2, is the optical equivalent of a cache memory system. A cache memory in an electronic digital computer reduces memory read time by providing direct access to a region of the memory by the microprocessor. In an optical system, the cache memory concept will be even more important in high speed reading of optical memories.

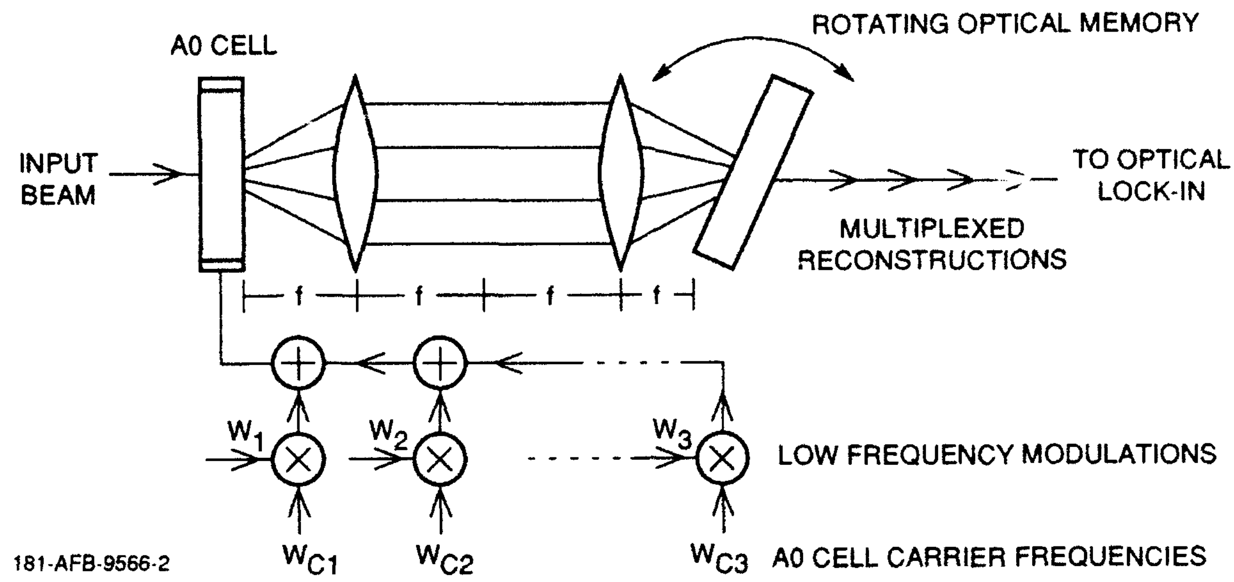

Figure 2. The optical cache memory. An acousto-optic cell is used to address a selectable range of angle multiplexed holograms. The range is selectable by rotating the optical memory. A small group of reconstructions is then converted to temporal multiplexing

The optical cache memory can be used to address a particular angular region of an angle multiplexed volume hologram, thus selecting a small group of holograms in parallel. This can be realized using an acousto-optic cell (AO cell) to create a small number of beams at various angles from a signal beam, as seen in Figure 2. Each of the beams exiting the AO cell have an additional distinct low frequency modulation. An optical lock-in detector is used to provide fast parallel access to any of the small group of holograms reconstructed in this manner. Since no mechanical movement is involved, this access can be faster than rotating the hologram or mirrors. In addition the selected group of reconstructions are all available at the same time. This report will provided a simple description of the operation of this device and a demonstration of its use.

The following is a brief overview of the system. As modeled in Figure 3, we start with angle multiplexed holograms in some volume recording media. Each hologram is simultaneously addressed at their respective angle and phase modulated to produce a reconstruction beam carrying all of the holograms by temporal multiplexing. This multiplexed beam acts as the signal input to the optical lock-in detector. Here, the reference beam of the

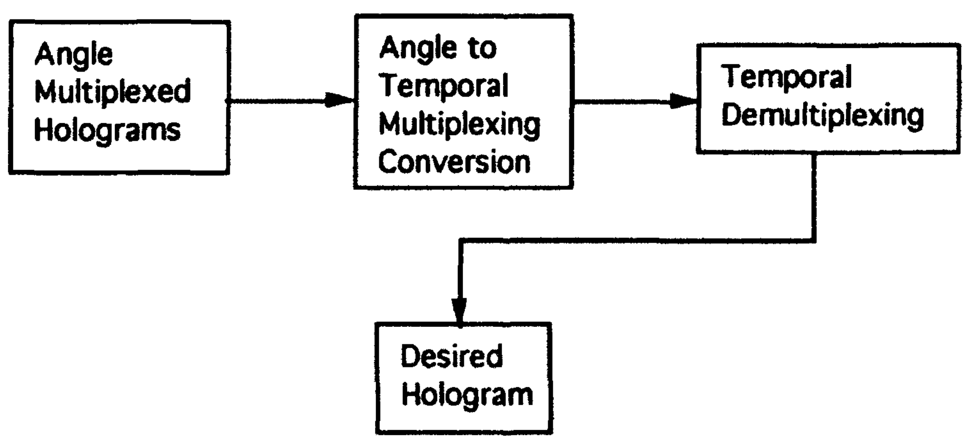

Figure 3. Overview of System for Accessing Angularly Multiplexed Holograms Stored in an Optical Medium

optical lock-in is phase modulated to selectively match one of the modulated holograms to produce an output beam which carries the desired hologram.

1.2 Summary of Phase I Results

The original tasks for the Phase I program are listed below:

1. Create a sample storage medium containing at least two angle multiplexed holograms.
2. Observe the reconstruction of each hologram separately.
3. Construct an optical lock-in detector using Bismuth Silicon Oxide (BSO) as the mixing element and piezo-electric transducers (PZT) supporting mirrors to modulate the phase of the various beams.
4. Construct a system to demultiplex holograms produced by the angle to temporal multiplexing conversion.
5. Demonstrate the selective nature of this system.

All of these tasks were successfully carried out during Phase I, resulting in the experimental demonstration of a photorefractive lock-in detector for the reconstruction of individual holograms multiplexed on a single laser beam.

Two distinct holograms were first recorded in a single sheet of DMP-128, a unique holographic film that is being jointly exploited by Polaroid Corporation and Foster-Miller for optical interconnect applications. These two holograms consisted of the letters "USAF" and "FMI." Using the overall experimental setup shown in Figure 4, both holograms were then read out on a single optical beam, and this beam was incident on the BSO crystal which is at the center of the photorefractive lock-in. Using four wave mixing, the original multiplexed holograms are reflected and can be viewed by a CCD camera as shown in the figure. Figure 5 illustrates the results with no phase modulation applied to any beam and indicates that both holograms are present on the beam simultaneously. To demonstrate the operation of the lock-in, we modulate the "FMI" hologram at 133 Hz and the "USAF" hologram at 177 Hz using the mirrors mounted on piezo-electric controllers and select one hologram or the other for viewing by modulating the reference

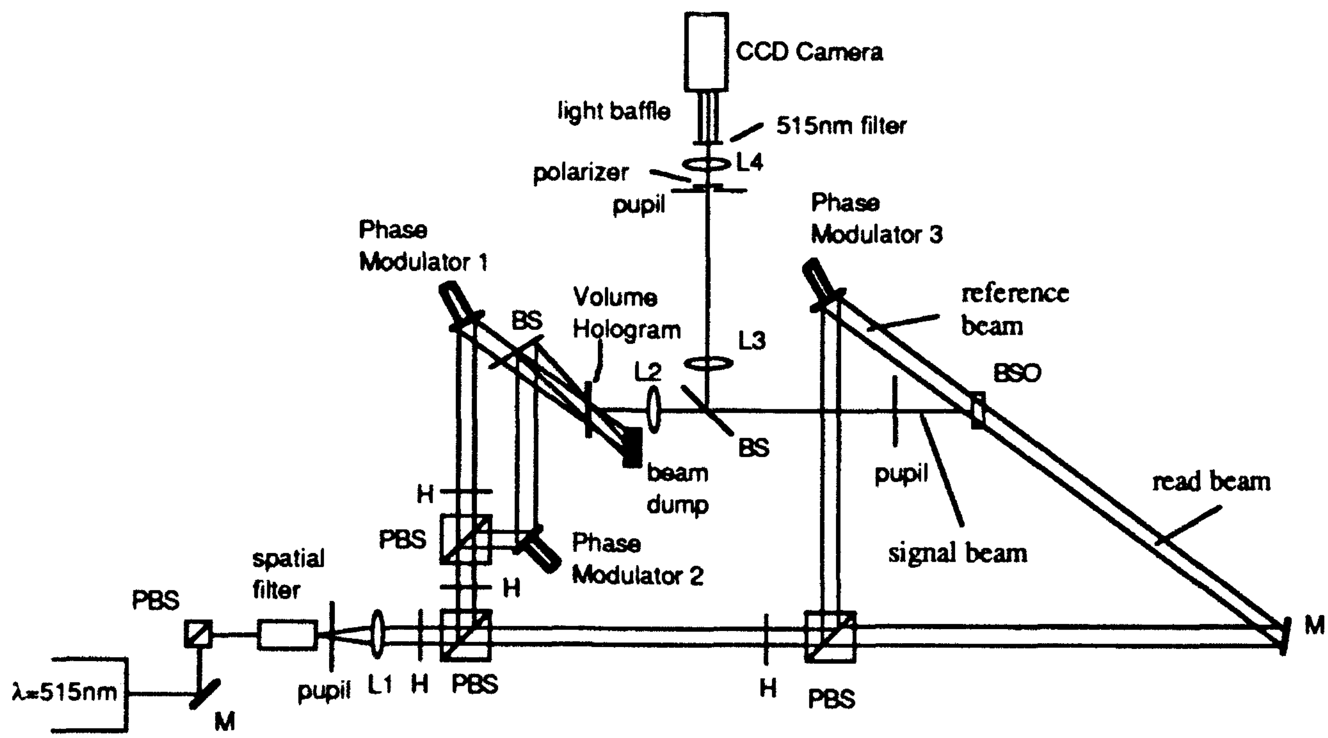

Figure 4. The Experimental Setup Used to Demonstrate the Optical Lock-In Detector for Demultiplexing Holograms

Figure 5. Video output from the system shown in Figure 4 with no modulation applied to any beam. Both holograms, 'FMI' and 'USAF,' are simultaneously present on the beam and are not demultiplexed

beam. Figures 6 and 7 show the video output of the system with phase modulation of 133 Hz or 177 Hz, respectively, applied to the read beam. The demultiplexing of the two holograms is complete with no cross talk visible in these images. Section 2 describes our experimental procedures and results in detail.

1.3 Recommendations for Phase II

For Phase II we recommend the development of a prototype optical memory system based on prior and ongoing research by Foster-Miller in optical storage media, optical interconnects and the optical lock-in demultiplexer. Foster-Miller

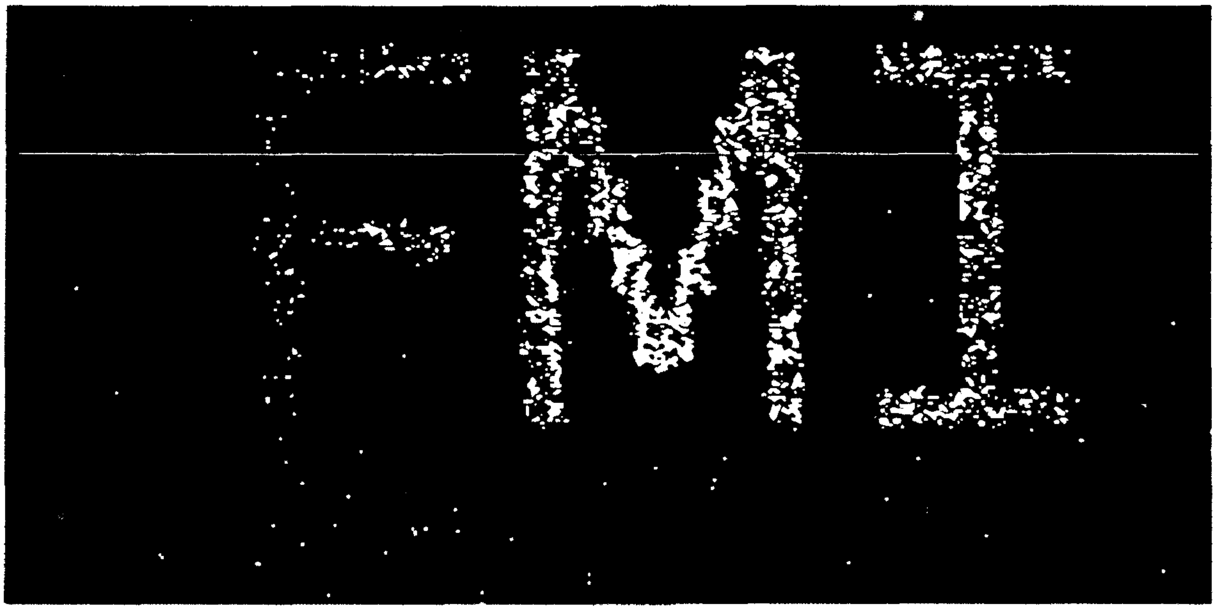

Figure 6. Video output of the system adjusted to demultiplex the holograms and select 'FMI.' 'FMI' phase modulation = 133 Hz, 'USAF' phase modulation = 177 Hz, and reference phase modulation = 133 Hz

Figure 7. Video output of the system adjusted to demultiplex the holograms and select 'USAF.' 'FMI' phase modulation = 133 Hz, 'USAF' phase modulation = 177 Hz, and reference phase modulation = 177 Hz.

currently has several programs in related areas to optical memories in addition to the optical lock-in detector. These programs address both the material for holographic optical data storage and the important problem of efficient interconnects to the optical memory. When combined with the optical lock-in detector demonstrated in Phase I, it is possible to demonstrate a prototype optical memory system with a unique and efficient accessing approach. Foster-Miller is currently performing research on the optical interconnect portion of this system with Polaroid Corporation, and this joint effort could be an important path to Phase III commercialization of concepts developed during Phase II.

Figure 8 illustrates the basic approach to efficient parallel access to an optical 3D memory with holographic data storage. An input laser

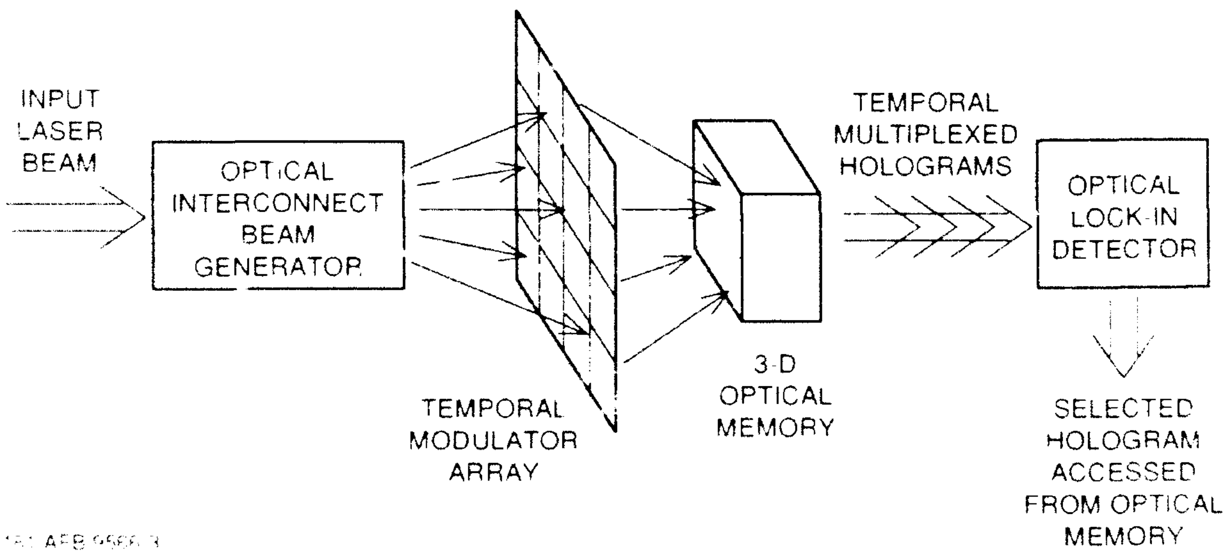

Figure 8. System for efficient parallel access to an optical 3D memory employing angularly multiplexed holographic data storage. Angular multiplexing is converted to temporal multiplexing which is readily demultiplexed using the optical lock-in

beam is divided into a controlled two-dimensional array of beamlets using a dynamic holographic array technique demonstrated at Foster-Miller under an Air Force Rome Laboratories Phase II SBIR program. This optical interconnect system uses a special holographic film, DMP-128 from Polaroid Corporation, that is infused with liquid crystals (LC). Application of a voltage to the LC/DMP composite allows the holograms stored in the DMP layers to be turned on or off. By using a layer of multiple thin controllable holograms, we are able to create the equivalent of a thick, *dynamic* hologram which can create a tunable array of beamlets. The subsequent array of beamlets will exit the DMP composite at controlled and selectable angles and will be modulated with a 2D array of modulators, either acousto-optic or electro-optic. After subsequent lensing the beams are then incident on the optical memory material which already contains a large number of stored holograms.

The optical memory may consist of existing materials, such as $LiNbO_3$, or one of the new photorefractive composites now under development at Foster-Miller. These new materials are based on polymers with a proprietary mixture of dye and other optically active materials. Initial results from these materials have been very positive, with high diffraction efficiencies measured using polymers that can be manufactured at a fraction of the cost of present competing materials. It is Foster-Miller's intention to pursue commercialization on these polymer memory materials in Phase III.

Referring again to Figure 8, the simultaneous reading of multiple holograms from the memory results in an output beam of overlapping holograms, each modulated at a separate frequency. The optical lock-in detector is then used to select one hologram as output using an optical technique that is entirely non-mechanical. The result is fast and efficient access to a complete angular range of holograms stored in the 3D optical memory.

While storage of multiple holograms in optical memory materials has been addressed by a number of researchers over the past several years, there has been limited progress in achieving rapid access to stored holograms. The approach suggested in this report will demonstrate an important first step in development of a fast and efficient, non-mechanical system for memory access. This prototype integrated system, consisting of optical interconnect, optical memory, and optical lock-in detector, will be described in detail in the forthcoming Phase II proposal.

2. PHASE I EXPERIMENTAL RESULTS

2.1 Volume Hologram

2.1.1 Angular Multiplexing

In recent years, optical memory research has centered on storage of multiple holograms in volume recording media such as $LiNbO_3$ and other photorefractives. One of the more common approaches is angular multiplexing of the holograms in the storage media. With this technique, cross talk in the reading of the holographically stored data is important. A key operating parameter for achieving low cross talk with multiple holograms in a volume (or thick) hologram is high Bragg angle selectivity. This is accomplished through the use of thick or volume holograms that have very narrow readout angular ranges. A thick hologram is defined by a recording media thickness that is much greater than the grating spacing formed by the interference of the two writing beams. In this approach, a number of holograms are recorded with distinct angles between the object and reference beams in order to produce reconstruction with little cross talk, as seen in Figure 9.

In order to demonstrate the use of the optical lock-in detector as an effective tool for reading optical memories, it was first necessary to record multiple holograms in some medium. Since the Phase I effort is necessarily somewhat limited in its scope, we chose to model an optical storage medium by recording two holograms in one holographic film. This was accomplished trying a 17 mm thick emulsion of Kodak 649F and an 8 mm thick emulsion of Polaroid DMP-128 to model a thick holographic medium. Kodak 649F was initially chosen for its ease of use. However, after making several attempts with various exposure levels to record in a step-by-step manner two angle multiplexed holograms, we were able to produce holograms with maximum efficiencies of less than 0.01 percent

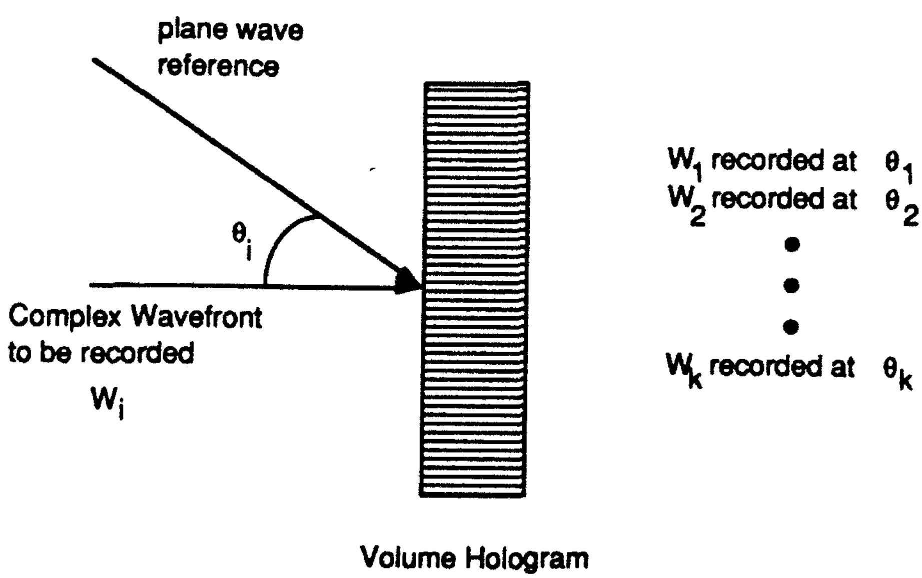

Figure 9. Angle multiplexing in a volume hologram. Each complex wavefront, W_i, is recorded with a distinct plane wave reference beam and an angle of q_i

even after bleaching. Single holograms can be recorded in the Kodak film with much higher efficiency, but apparently the efficiency is degraded for multiple exposures.

The DMP-128 film from Polaroid requires more processing steps, but in general is capable of very high diffraction efficiency, approaching 100 percent for single exposures. Foster-Miller is currently engaged in a joint effort with Polaroid to exploit the applications of this film. In this arrangement, Foster-Miller is actively engaged in exploring and demonstrating practical applications of the DMP-128 for optical interconnects, switching and related devices, and Polaroid is providing additional research to improve the film properties. Using the DMP-128, two holograms were recorded at separate angles in a step-by-step manner in this material. One of our attempts produced a recording of two angle multiplexed holograms with separate reconstruction efficiencies of 0.7 percent and 0.35 percent. For our modeling purpose, these efficiencies were expected to be effective.

2.1.2 Construction of the Angular Multiplexed Holograms

Foster-Miller has a darkroom and a humidity-controlled optics laboratory dedicated to the processing of DMP-128 holograms. The individual holograms are made using the following three film processing steps: activation, exposure, and development. Typically the films are received as 5 x 5 cm coated glass plates with a 3 to 15 μm thick layer of the DMP-128. The films are received in a light tight container with desiccant from Polaroid. In order to activate the material, it is transferred under safe light conditions to a humidity controlled chamber at Foster-Miller. A saturated solution of potassium thiocyanate in the chamber maintains a relative humidity of 47 percent +/- 2 percent. For a 5 x 5 cm film plate, the film is optimally activated when 1 mg of H_2O per micron of film thickness is absorbed. After activation the film plate is placed in a fixture and a thin film of xylene is formed on the film to seal the moisture in the film during exposure.

After stabilization, the film is exposed using the general arrangement shown in Figure 10. Typical exposures for transmission holograms made at 633 nm (HeNe) are 4 to 15 mJ/cm^2. The primary exposure is followed by a uniform blanket exposure from an incandescent lamp. Development involves a three step wet chemical immersion sequence followed by drying.

The holograms were created by exposing DMP-128 to the interference pattern produced by a beam carrying the image of the letters 'FMI' and a plane at an angle 22.8 deg with respect to image bearing beam. A second exposure was made

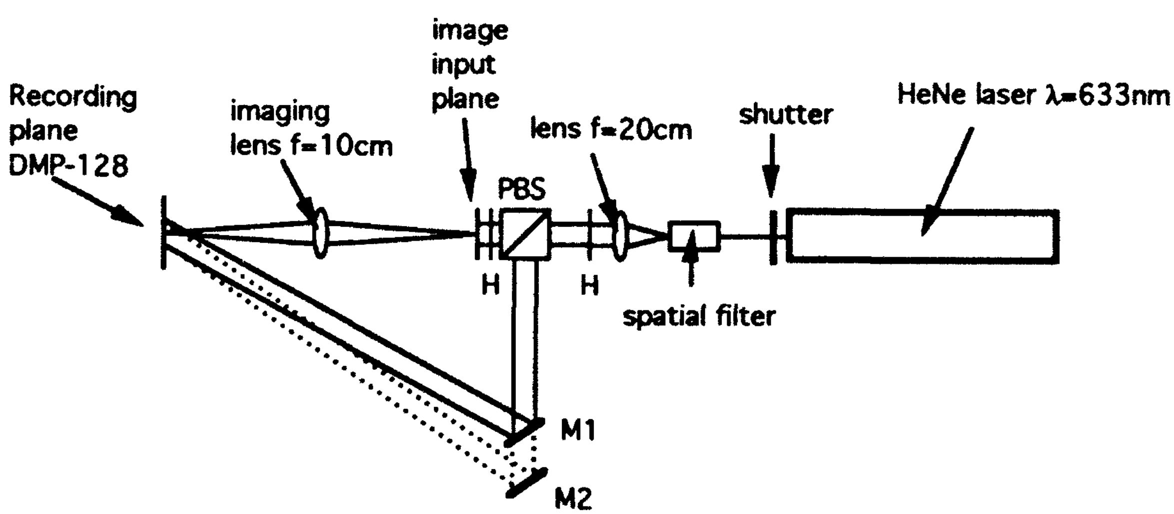

Figure 10. System used to record angle multiplexed holograms in Polaroid film DMP-128. The first exposure is made with a mirror at M1. The second exposure is made with a different input image and the reference beam reflected off a mirror at M2

with the image of the letters 'USAF' and plane wave reference at an angle 25.0 deg with respect to the image beam. Figure 10 illustrates the experimental setup used to make these recordings. The first exposure is made with a mirror at position M1. After the first exposure is completed, we change the input image and remove mirror M1 so as to produce a reference beam at a different angle. Both exposures were made at energies of 5 mJ/cm^2 using a HeNe laser.

This volume hologram has the property that when two beams are incident upon it at the same angles the recordings were made (i.e., 22.8 and 25.0 deg) the output reconstructions are collinear and therefore superimposed. This same construction can be extended to storage of multiple holograms.

2.2 Angular to Temporal Multiplexing Conversion

In order to implement the cache memory concept, we require an effective means of simultaneously addressing a region of holograms within a given angular spread. At least two techniques are available to accomplish this cache accessing. An AO cell has the ability to access each stored hologram at a different angle at the same time it produces a phase modulation in the audio/radio frequency range. As mentioned in subsection 2.1, the reconstructions are collinear and superimposed. With distinct modulating frequencies, the superimposed holograms become temporally multiplexed. Figure 11 identifies an example of converting angle multiplexed holograms to temporal multiplexed holograms with sinusoidal phase modulations applied to each individual complex wavefront. An alternative to the AO cell approach is to use the optical interconnect approach presently under development at Foster-Miller which uses tunable, dynamic holograms made from liquid crystal infused DMP-128. This beam generator, which has been briefly described in Section 1, is capable of producing different sets of optical beams for addressing different angular areas of the optical storage medium. Acousto-optic or electro-optic modulators can then provide the phase modulation required to use the optical lock-in detector.

In our experiment, we modeled the use of an AO cell for the conversion with mirrors supported on piezo-electric transducers (PZT) and with a beam splitter to address the DMP-128 storage hologram at two separate angles and two separate phase modulations. The PZT supported mirrors (PZM) required very stable precision mounts in order to avoid any mount resonances with can detract from the intended phase modulations. As seen in Figure 12, a 1 in. diam circular first surface mirror is attached using a strong adhesive to the moving piston of the PZT assembly. The PZTs are model PZL-007 from Burleigh

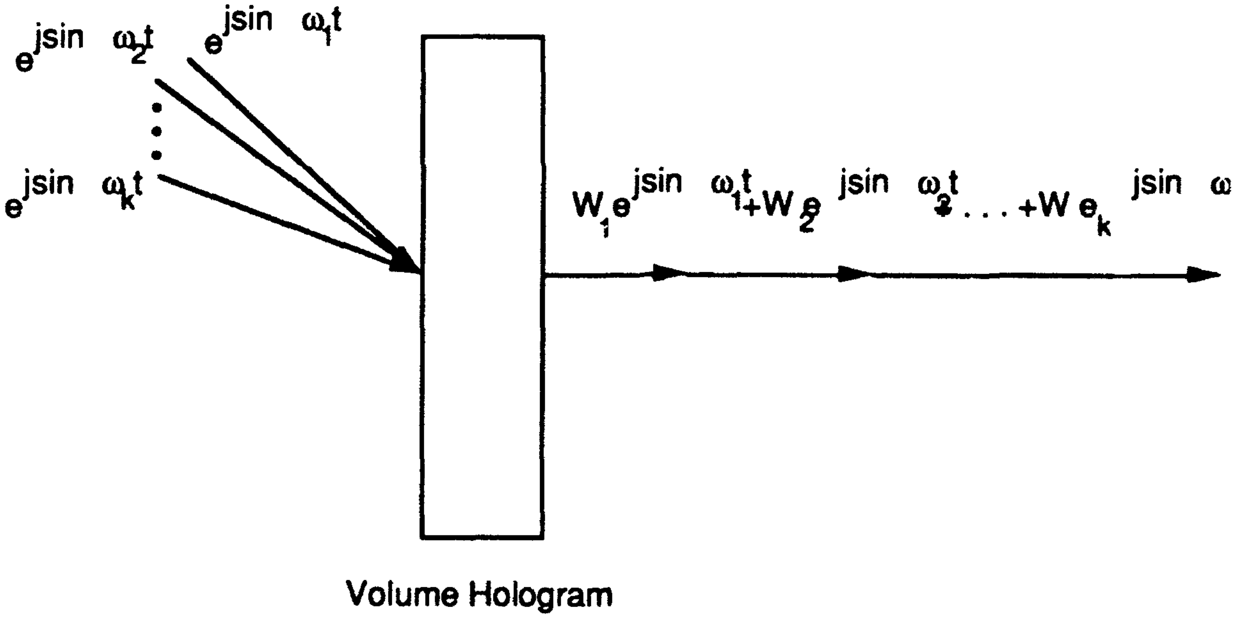

Figure 11. An example of angle to temporal multiplexing conversion. The volume hologram is recorded as discussed in subsection 2.1

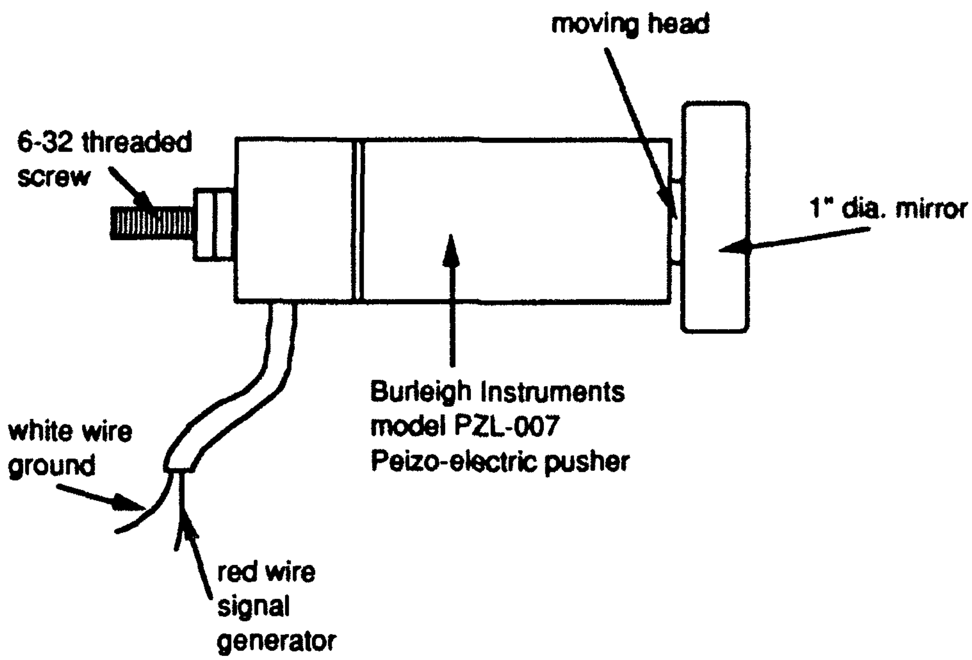

Figure 12. Phase Modulator Constructed from a Mirror Supported by a PZT Modulator

Instruments. The housing of the PZT assembly has a 6-32 bolt attached to it. The 6-32 bolt is used to fasten the entire subsystem to a tilt stage made with strong springs.

2.3 Temporal Demultiplexing

These temporally multiplexed holograms can be demultiplexed using an optical lock-in detector. The optical lock-in detector is a device which is based on a modified version of four-wave mixing in a photorefractive media. Reference (3) contains a detailed discussion of the theory. The following paragraph offers a brief description, sufficient for the purposes of conveying the demultiplexing capabilities.

When two beams, signal and reference, are intersected within a photorefractive media, they create an interference pattern assuming they are coherent and have the same linear polarizations. In our experiments, we used bismuth silicon oxide ($BiSO_3$, BSO) as the photorefractive mixing element. A phase grating is formed through the photorefractive effect with a response time t. (For BSO, response times are on the order of 10 ms.) If a modulation, in this case a phase modulation, is added to the signal beam at a frequency f_1, which is greater than the inverse response time of the BSO, a moving interference pattern is created which does not allow enough time for a phase grating to form. This is witnessed by reading the photorefractive grating with a beam at the same wavelength as the writing beams traveling in a counterpropagating direction to the reference beam and at an orthogonal polarization to the write beams. An output beam is diffracted off the grating and travels in a counterpropagating direction to the signal beam and can be separated with a beam splitter for analysis. With no phase modulation, the output beam is simply the conjugate of the signal. However, when the signal beam is modulated with a PZM, the grating is erased and there is no optical output.

We may stabilize the moving interference pattern, produced by modulating the signal beam, by modulating the reference beam at a frequency f_2. If the difference between the two modulating frequencies is much less than the inverse response time of the photorefractive, then an oscillating grating is produced which oscillates at the difference frequency. (Also resulting in the output phase conjugate oscillating since its field amplitude is proportional to the grating strength.) If the difference is zero, then the grating becomes stable and the output phase conjugate is stable. A model of an optical lock-in detector is presented in Figure 13, and a summary of the effects produced by the modulations is listed in Table 1.

This principle may be extended to modulating multiple signal beams at distinct frequencies, all superimposed into one optical beam, as is the case of the temporally multiplexed holograms in

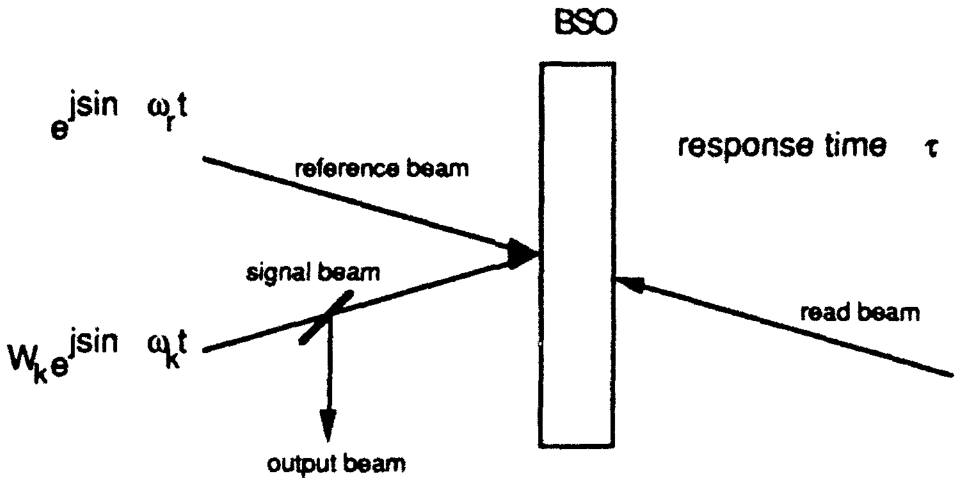

Figure 13. The Optical Lock-In Detector

Table 1. Summary of the Effects Produced by Modulations

Reference Beam Modulation ω_1	Signal Beam Modulation ω_2	Interference Pattern	Difference Frequency $\Delta\omega=\omega_1-\omega_2$	Grating	Output
None	None	Stable	$\Delta\omega<<1/\tau$	Stable	W
Phase at ω_1	None	Moving	$\Delta\omega>1/\tau$	Erased	None
Phase at ω_1	Phase at ω_2	Moving	$\Delta\omega>1/\tau$	Erased	None
Phase at ω_1	Phase at $\omega_2 \cong \omega_1$	Stable	$\Delta\omega<<1/\tau$	Stable	W

subsection 2.2. Then, the reference beam's modulation frequency can be tuned to lock-in a particular desired signal (hologram).

2.4 Experimental Results

The components described in the prior sections were combined to form a complete holographic multiplexing/demultiplexing system. In this section, a description of the overall experimental setup and results is presented, demonstrating the ability of the optical lock-in to demultiplex modulated holograms.

2.4.1 System Implementation

In the laboratory we fabricated the required devices, including the volume hologram and phase modulators as described in subsections 2.1 and 2.2. A single laser line at 515 nm from an argon laser was spatially filtered and expanded to a collimated beam by lens L1, as illustrated in Figure 4. Half wave plate, H, is used to control the ratio of the two beams exiting the polarizing beam splitter, PBS. The reflected beam is sent through a second set of a half wave plate and a PBS in order to produce two beams to address the volume hologram. The mirrors supported on PZTs then reflect these beams to a beam splitter, BS, where they are combined at different angles. The half wave plate prior to the first phase modulator is used to make the beam's polarization the same as the vertical polarization of the second addressing beam. Each beam is incident upon the volume hologram to produce two distinct copropagating reconstructions. The volume hologram contains angle multiplexed recordings of the letters 'FMI' and 'USAF' in DMP-128 (as described in subsection 2.1). Lens L2 images these reconstructions to the BSO to form the signal beam for the optical lock-in detector. A pupil is placed around this beam to block off-axis beams.

Returning to the first PBS we encounter, the beam which passes through it is sent to a third half-wave plate and a PBS. The beam which is reflected off of this PBS is vertically polarized and directed towards a third mirror attached to a PZT. This beam is then reflected to the BSO and acts as the reference beam in the optical lock-in. The beam which passes through the third PBS is reflected off a mirror to produce the read beam which is horizontally polarized and counterpropagates the reference beam. This beam will read out any grating formation in the BSO, thus producing the output phase conjugate beam which counterpropagates the signal beam. In the experiments, the complete signal beam intensity incident upon the BSO was 0.2 mW/cm^2, the reference beam intensity was 3.2 mW/cm^2 and the read beam intensity was 1.8 mW/cm^2. The phase conjugate is separated from the signal with a beam splitter. Lenses L3 and L4 image and demagnify the output beam to a CCD camera. A pupil, analyzing polarizer, 515 nm line interference filter and a light baffle are all used to increase the signal-to-noise ratio of the output beam incident on a Sony model XC-75 CCD camera. The output video signal is viewed on a monitor and data is captured using NIH Image software on a Macintosh II personal computer with an acceleration board. Electronic signal generators are available to drive the PZTs. Figure 14 is a photograph of the experimental system illustrated in Figure 4.

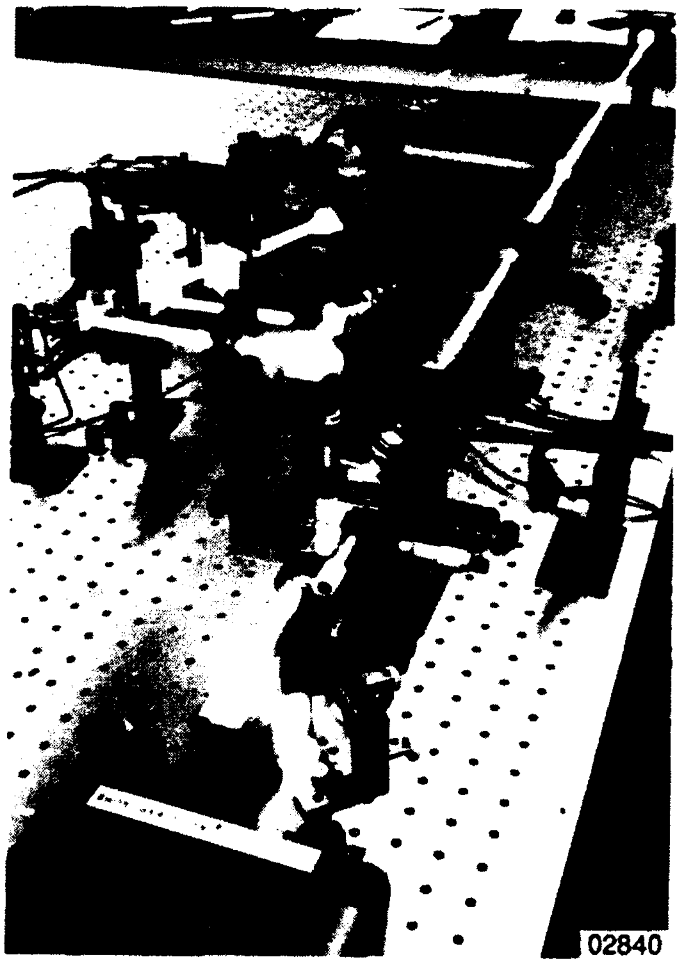

Figure 14. Photograph of the Experimental System Illustrated in Figure 4 and Used to Demonstrate the Use of the Optical Lock-In to Demultiplex Holograms

2.4.2 Analysis of Experimental Results

The goal of our first experiment with this completed system was to show its ability to select one hologram among the two stored holograms. The PZTs for the first and second phase modulators were driven by two separate signal generators producing a sine wave each with amplitudes of 2.8V which is large enough to produce erasure of the grating in the BSO if operated alone. The first PZT was operated at a frequency of 133 Hz and the second was operated at 177 Hz. The driving signal for the third PZT used to phase modulate the reference beam is derived from either the signal generator driving the first PZT or the generator for the second PZT, selectable by a switch. This was done to ensure the reference modulation was exactly matched to a signal modulation. Typically, one could also achieve this with a third signal generator triggered to one of the signals.

Figure 5 shows the output of the CCD camera when no modulation is applied to any beam. As expected, the result is the phase conjugate of the signal beam which displays the two stored holograms superimposed upon another. When we apply the modulation, with the reference modulation selected to match the modulation of the first phase modulator, the resulting output is only the image of the letters 'FMI' as seen in Figure 6. Since the first phase modulator is used to address the hologram which stored the 'FMI,' this is the result we had expected. When the reference modulation was switch to match the second phase modulator, the output displays the letters 'USAF' as seen in Figure 7. Again, this is expected since the second phase modulator is used in addressing the hologram which contains the letters 'USAF.' Thus we were able to select a stored hologram by changing the modulation of the reference beam to match the modulation of a desired reconstruction.

Our second experiment was done to show the channel separation of the two phase modulated reconstructions. The first and second phase modulators were driven with distinct sine wave signals at 133 Hz and 177 Hz with an amplitude of 2.8V. The third phase modulator is driven with a third signal generator which generates a sine wave at an amplitude of 2.8V. The third signal generator is set to sweep through a range of frequencies from 127 Hz to 187 Hz. As the sweeping is taking place we observe the video output of the system on the monitor. When the reference modulation is between approximately 127 Hz and 147 Hz, we observe the output of the image containing the letters 'FMI' oscillating at the frequency equal to difference between the reference modulating frequency and 133 Hz. When the reference modulation is in range of 167 Hz to 187 Hz we observe the same oscillations with image containing the letters 'USAF.' This experiment points out the channel separation for the reconstructed holograms needs to be about 20 Hz when we use BSO as our mixing element.

3. CONCLUSION

A new system architecture for addressing large capacity angle multiplexed volume holograms has been presented and demonstrated experimentally. The architectures relies on converting angle multiplexed holograms to temporal multiplexed holograms which can be accomplished using an acousto-optic cell or a dynamic holographic interconnect system being developed by Foster-Miller on another program. For demonstration purposes, we modeled the use of the AO cell or optical interconnect system with simple optics and piezo-electric driven mirrors. After conversion of the stored angle multiplexed holograms to temporal multiplexed reconstructions of the holograms, an optical lock-in detector was used to successfully demultiplex and separate the individual holograms. This system architecture allows for fast parallel access of the stored information in a region of a holographically-stored optical memory without mechanical operations. Our system is analogous to a cache memory in electrical systems and is an important first step in solving the difficult problem of high speed access to 3D optical data storage.

In our experiments, we fabricated a volume hologram containing two angle multiplexed wavefronts. These holograms were readout simultaneously, phase modulated and demultiplexed using the photorefractive crystal BSO. In theory, this architecture has the ability to access information on the order one channel per microsecond, where the system can accommodate 10^{13} channels and each channel carries a hologram which can be encoded with 2 Mb of information.

In Phase II we propose to construct a prototype optical memory system which consists of an optical interconnect system using dynamic holography, a unique optical memory material developed at Foster-Miller, and the optical lock-in detector. This approach will demonstrate an important first step in development of a fast and efficient, non-mechanical system for memory access. The prototype integrated system, consisting of optical interconnect, optical memory, and optical lock-in detector, will be described in detail in the Phase II proposal.

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APPENDIX A

PHOTOREFRACTIVE OPTICAL LOCK-IN DETECTOR

Photorefractive optical lock-in detector

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An optical lock-in detector has been proposed and demonstrated. This scheme utilizes the multiplicative and low-pass filtering characteristics of four-wave mixing in $Bi_{12}SiO_{20}$.

In many scientific, commercial, and industrial applications it is necessary to detect and recognize signals that are embedded in a high-noise environment. Some of these applications may include communications, spectroscopy, and measurement of the Hall effect and may further include biomedical applications.[1,2] One of the more useful instruments for these applications is the lock-in amplifier. In certain cases, such as in the study of noisy images for which the signal and the noise have different temporal frequencies and in interferometric techniques for thin film analysis[3] when the signal is already optical, it is better to develop an all-optical device that would be parallel in its performance.

Traditionally a lock-in detector is a combination of a frequency mixer followed by a low-pass filter. Mixing two signals of frequencies f_1 and f_2 generates signals of frequencies $f_1 + f_2$ and $f_1 - f_2$ and their integer multiples. Low-pass filtering yields a signal with the beat frequency $f_1 - f_2$.

Both multiplication and lock-in detection can be realized optically by using photorefractive four-wave mixing (FWM).[4] The multiplicative characteristic of FWM is used for mixing, and the response time of the photorefractive medium is used for low-pass filtering.[5]

In this scheme one reference beam is temporally phase modulated at a frequency f_1, which is much higher than the reciprocal of the crystal response time. The signal beam is phase modulated at a slightly different frequency, f_2. The modulation in both beams results in the phase-conjugate beam's oscillating in amplitude at the frequency $f_1 - f_2$. The amplitude of the oscillating phase conjugate is higher at low beat frequencies and vanishes when the beat period becomes much shorter than the photorefractive response time. When both the signal and the reference beams are modulated with the same period by similar or different waveforms, the result is a nonoscillating phase conjugate whose intensity is determined by the phase difference between the two input modulating signals. We show that this parallel optical lock-in detector is analogous to the serial electronic phase-sensitive detector or lock-in detector.

Another device that operates on the principle of processing signals that vary faster than the response time of the material is the time-integrating optical correlator.[6]

Consider a photorefractive material in which three beams, A_1, A_4 (the reference and the signal beams, respectively), and A_2 interact through FWM. A space-charge field (E_{SC}) is built up, and a phase-conjugate beam, A_3, is generated.[7] The photorefractive equation that describes the development of the space-charge field within the crystal, assuming that A_1 and A_4 are coherent, is given by

$$\frac{\partial E_{sc}}{\partial t} + \frac{E_{sc}}{\tau} = \frac{G}{\tau}\frac{A_1(t)A_4^*(t)}{I_0}, \tag{1}$$

where τ is the response time of writing the grating, G is a parameter that can be found from standard theories of the photorefractive effect,[8] and I_0 is the total intensity of the interacting beams:

$$I_0 = |A_1|^2 + |A_2|^2 + |A_3|^2 + |A_4|^2 = \text{const}.$$

For weakly absorbing materials with small electrooptic coefficients, constant I_0, and a time-independent readout beam, the Kogelnik[9] theory yields a phase-conjugate amplitude that is proportional to the space-charge field:

$$A_3 \propto E_{sc}.$$

Assuming that the specific case in which the two input beams A_1 and A_4 are sinusoidally phase modulated at frequencies large compared with the reciprocal response time of the material, one has

$$A_1 = |A_1|\exp[-i\delta_1 \sin(\omega_1 t + \phi_1)] = |A_1| \sum_{-\infty}^{\infty} J_n(\delta_1)\exp[-in(\omega_1 t + \phi_1)], \tag{2a}$$

$$A_4 = |A_4|\exp[-i\delta_2 \sin(\omega_2 t + \phi_2)] = |A_4| \sum_{-\infty}^{\infty} J_n(\delta_2)\exp[-in(\omega_2 t + \phi_2)], \tag{2b}$$

where δ_1 and δ_2 are the amplitudes of the phase modulations in beams A_1 and A_4, respectively, and ω_1 and ω_2 are the phase-modulation frequencies. The signal phases are ϕ_1 and ϕ_2 and J_n is the nth-order Bessel function. Substituting Eqs. (2) into the solution for Eq. (1) yields

$$E_{sc} = \frac{G|A_1||A_4|}{I_0\tau} \sum_{n=-\infty}^{\infty} \sum_{m=-\infty}^{\infty} \left\{ \frac{J_n(\delta_1)J_m(\delta_2)}{i(n\omega_1 - m\omega_2) + 1/\tau} \times \exp[-i(n\omega_1 - m\omega_2)t]\exp[-i(n\phi_1 - m\phi_2)] \right\}. \tag{3}$$

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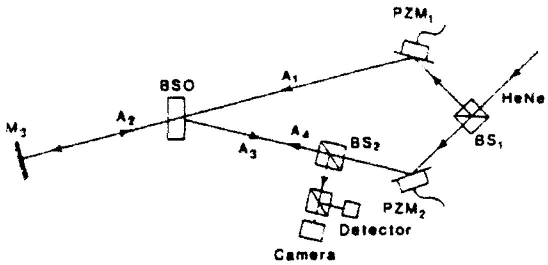

Fig. 1. Experimental arrangement used for frequency mixing and optical lock-in detection.

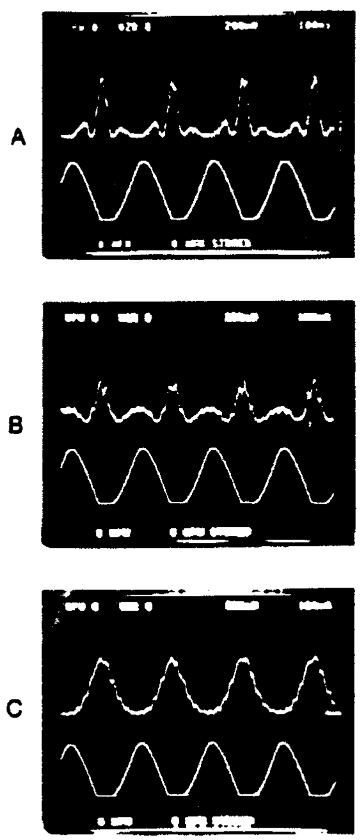

Fig. 2. Six oscilloscope traces displaying the results of sinusoidal phase modulation. The bottom trace of each pair shows the electronic results. A, Both inputs are modulated at 10.8 rad. B, The two inputs modulated simultaneously by 10.8 and 5.4 rad. C, Both of the inputs are modulated by 5.4 rad. The horizontal axis in all cases is 100 ms/division.

Because of the low-pass-filtering characteristics of the photorefractive medium, the only terms that have significant contributions are the terms that satisfy the relation

$$(n\omega_1 - m\omega_2)\tau \ll 1.$$

Since the oscillation frequencies are assumed to be large compared with the reciprocal response time of the photorefractive material, the only terms that contribute are the $n = m$ terms, and

$$E_{sc} = \frac{G|A_1||A_4|}{I_0\tau}\sum_{n=-\infty}^{\infty}\left\{\frac{J_n(\delta_1)J_n(\delta_2)}{in(\omega_1-\omega_2)+1/\tau} \times \exp[-in(\omega_1-\omega_2)t]\exp[-in(\phi_1-\phi_2)]\right\}. \tag{4}$$

For reference frequencies, $\omega_1 = \omega_2$,

$$E_{sc} = \frac{G|A_1||A_4|}{I_0}\sum_{n=-\infty}^{\infty} J_n(\delta_1)J_n(\delta_2)\exp[-in(\phi_1-\phi_2)]. \tag{5}$$

For $\omega_1 = 2\omega_2$ it is possible to show that the second harmonic of A_1 couples with the first harmonic of A_4, as is the case in electronic lock-in detectors.[1]

It is clear from Eq. (5) that, when the fields A_1 and A_4 are modulated at frequencies higher than the reciprocal response time of the material, the output is dependent on the phase difference between the two input signals and their amplitudes. This is the principle of optical phase-sensitive detection.

The experimental arrangement for demonstration of the underlying ideas and comparison with theory is shown in Fig. 1. It is essentially a standard configuration of FWM modified by two mirrors mounted upon piezoelectric transducers (PZM_1 and PZM_2) in the reference and signal beams. A 30-mW He–Ne laser beam was expanded to a radius of 2 mm and divided into two input beams by beam

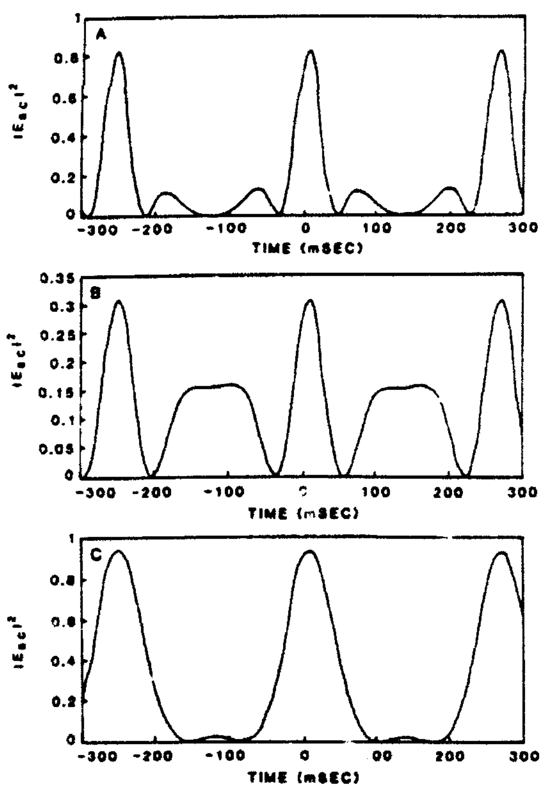

Fig. 3. Theoretical prediction of the oscilloscope traces in Fig. 2.

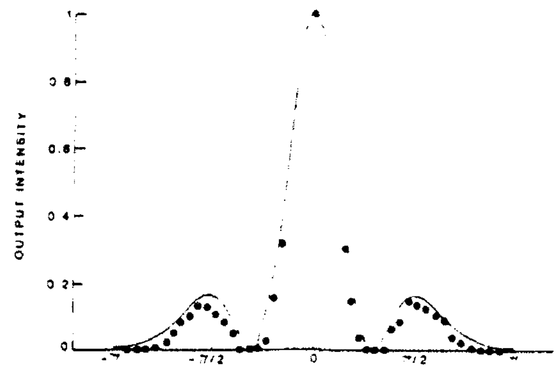

Fig. 4. Intensity of the phase-conjugate return as a function of the phase difference in the two electronic driving signals. The dots represent the experiment, and the solid curve represents the theory.

splitter BS_1. The intensity of the reference beam was I_1 = 59 mW/cm^2, and the intensity of the signal beam was I_4 = 82 mW/cm^2. The beams intersect in a $Bi_{12}SiO_{20}$ (BSO) crystal at an angle of 18°. The reference beam after its passage through the crystal was reflected back to the BSO crystal to generate a readout beam of I_2 = 38 mW/cm^2. The phase-conjugate beam A_3 was detected simultaneously by a photodetector and a camera.

Figure 2 shows three oscilloscope traces of frequency mixing between two sinusoidal phase modulations. The modulation on PZM_1 was at a frequency of 161 Hz, and the modulation on PZM_2 was at a frequency of 165 Hz. In Fig. 2A the top trace shows the result when both piezoelectric transducers were modulated so that the total phase modulation was 10.8 rad. We emphasize that any one of the phase modulations alone was able to destroy the phase-conjugate beam. The output signal consists of a high peak intensity with two low peak intensities. When the phase modulation of any one of the beams was reduced to half of its original amplitude, the previous two low peaks in Fig. 2A merged into one low peak, as illustrated in the top trace of Fig. 2B. By changing the modulation in both inputs to 5.4 rad, we observed a significant change and the result of the frequency mixing, which looks like the distorted sine wave shown in Fig. 2C.

Corresponding theoretical solutions are shown in Fig. 3. These are calculated from Eq. (4), assuming that τ = 10 ms and $\Delta\omega$ = 0.02416 rad/ms. To show that the frequency of the mixed signal is the beat frequency, we fed the two triggers of the driving signals to an electronic multiplier. The electronic results are illustrated in any one of the bottom traces of Figs. 2A–2C. A semiquantitative agreement between the theory and the experiment has been achieved.

Figure 4 shows the results of the phase-sensitive detector when it is operated simultaneously with two phase-locked sinusoidal phase modulations with shifts of 10.8 rad in both piezoelectric modulators at a frequency of 162.5 Hz. The solid curve is the theoretical plot from Eq. (3). In these calculations it was assumed that the response time of the material is 10 ms, which corresponded to the faster of the two response times of BSO.[10] Nine pairs of Bessel functions were included in the calculations. A good agreement between the experiment and the theory was achieved.

The object of this study is to introduce and demonstrate the principle of the optical lock-in detector. Even though the use of sine waves to modulate the phase of the reference and the signal beams is not optimal for self-referencing of the output, an exact self-reference can be obtained with a square wave modulating the phase of the reference beam and a sinusoidal amplitude modulation of the signal beam. In this sense, the output is linearly proportional to the amplitude of the input, which is the case in the electronic analog.[1]

An obvious follow-up to these experiments would be to design a device with pulse-width modulation in the reference beam to avoid coupling in the second harmonic. In addition, heterodyne detection would be possible by applying an external electric field across the crystal, resulting in a complex response time.[8]

In conclusion, we have proposed and demonstrated what is to our knowledge the first optical lock-in detector. This scheme utilizes the multiplicative characteristic of the real-time holographic medium as well as the low-pass-filtering property imposed by the response time of the material. Developing this device with the use of diode lasers and semiconducting photorefractive materials may open up the possibility of a new generation of optical phase-sensitive detectors that can process spatial and serial information. Using a material with a large electro-optic coefficient (such as $BaTiO_3$ or SBN) will provide gain, therefore permitting consideration of use of some real-time holographic media in an optical lock-in amplifier.

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